Ultra-low supply voltage crystal quartz oscillator

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ABSTRACT

In this paper, an ultra-low-voltage crystal quartz oscillator is proposed. The design of the proposed oscillator is essentially based on using a HEMT operating in an unsaturated dc regime and a quartz resonator as a resonant impedance transformer. The 25 MHz prototype shows steady oscillations at the supply voltage of less than 17 mV and the power consumption as low as 300 nW, i.e., 1–2 orders of magnitude lower than the other to-date oscillators. This approach is good for building ultra-low consumption radio devices including those working at low temperatures.

A reduction in the supply voltage is one of the most distinct modern trends in the development of digital and analog low-power electronics, in both mobile and stationary applications. New semiconductor technologies and circuitries are currently under development.[1,2] The quartz crystal oscillator is a core functional unit, which is of strong interest to developers from the point of view of lowering its consumption power and supply voltage.[3,4] To date, the supply voltage as low as 0.2 V and consumption power down to 7 μW for the radio frequency quartz crystal oscillator are achieved.[3] In our paper, we propose a specific and effective approach to designing an ultra-low supply voltage quartz crystal oscillator. The main goal of this work is to determine the limitation in the supply voltage reduction.

Considering a generator as an amplifier with positive feedback, one should choose an active element that has the maximal gain at a minimal supply voltage. We believe a field-effect transistor (FET) to be the most promising candidate for such an element. The FET's current channel contains no potential barrier (p–n junction). Accordingly, the current-driving drain–source voltage U_{ds} has no threshold. However, more important thing is the electrostatic principle of the channel conductivity control. At frequencies much lower than the FET's cut-off frequency F_t, the transistor control circuit (gate–source) consumes very low active power that ensures high current gain. This provides noticeable power gain G_p even at the voltage gain G_u being much smaller than unity that is typical for $U_{ds} < 0.5$ V.

In papers[5–7] devoted to FET operation in the unsaturated mode, it was shown that the minimal required drain–source voltage $U_{\min}$ for a fixed G_p decreases when decreasing the operating frequency F (more precisely, the F/F_t ratio). When the FET's complex input impedance perfectly matches that of a signal source, $U_{\min}$ is proportional to F.[5,6] Near-perfect matching of high-frequency small-signal FETs is realizable at frequencies above, roughly, 100 MHz. The quasi-matching is more common for lower radio frequencies when the magnitudes of the source and source–gate FET's impedances are equal. In this case,[7] $U_{\min} \sim \sqrt{F}$. These laws are principally due to the electrostatic modulation of the conduction of any-FET current channel, while the exact frequency varies depending on the specific class of FETs. The net parameter to compare the amplifying characteristics of differently designed FETs is the cut-off frequency F_t determined by the gate capacitance C and the transconductance G_m of the FET: $F_t = G_m/2\pi C$. The boundary frequencies for the most modern heterostructural FETs (HEMTs) are hundreds of gigahertz, so there is an undoubted possibility of a dramatic decrease in $U_{\min}$ for frequencies ranging from tens to hundreds of megahertz. As to amplifying devices, the feasibility of ultra-low voltage and power supply has been demonstrated repeatedly.[5–9] However, in the vast majority of cases, they were ultra-low-noise cryogenically cooled amplifiers and oscillators.[2] Here, we discuss ultra-low-power (ULP) self-excited oscillators that are operable both at cryogenic temperatures and under normal temperature conditions. The first results will be presented here to confirm the possibility of creating an important kind of electronic units and quartz oscillators with ultra-low supply voltage (10–100 mV) and consumption power (a few microwatts or less) for promising ultra-efficient radio devices.

The basis of our approach is to use a HEMT in a dc regime close to the unsaturated one. This mode, in contrast to the saturated microcurrent regime widely used in micropower electronics, is associated with moderate load values (hundreds of ohms), thus making it possible to build high-frequency devices. The near-unsaturated dc regime assumes the transistor operating point to be located in the upstream region of the current–voltage characteristics family. For this area, the transistor self-voltage gain (G_u, the product of the channel differential resistance by the transconductance) does not exceed unity in the linear amplification mode. When the transistor works as an active element of an oscillator, its operating point moves along the so-called "limit cycle" and can enter both drain current cutoff and fully open channel areas. The cycle-averaged G_u will further decrease. Therefore, the current amplification and the feedback loop, which provide the necessary output–input impedance matching with consequently greater-than-unity loop gain, are required. Let us consider the impedance matching task in more detail.

The perfect match in our case means maximizing G_p. Hence, the impedances of the transistor gate–source control circuit and the connected "signal source" circuit should be complex-conjugated. In the first approximation, the input circuit of a low-power HEMT with $F_t \approx 50$ GHz is modeled by using a capacitor $C \approx 0.5$ pF and a resistor $R_{gs} \approx 5\ \mathbf{\Omega}$ connected in series. It is clear that the matched source (LR circuit) must have a quality factor of more than 1000 ($F = 30$ MHz) that is not physically feasible with lumped-parameter elements. Even an inductor with a reactance of the order of 10 KΩ is unrealizable since its own resonance would lie in the frequency range below the operating one. The option of a distributed device (a resonator with a length of about 1 m) is obviously not realistic.

It is the crystal quartz resonator that actually has the required parameters. As well known, its equivalent circuit is a high-quality oscillatory tank circuit. By connecting such an element to the input (gate–source) of the transistor and partly coupling it to the output (drain–source), we implement a matching resonant impedance transformer. The phase condition for self-excitation is fulfilled by introducing a capacitive feedback element between the drain and the source of the transistor, similarly to the Colpitts oscillator.

The impedance matching performed in this way does not provide the perfect complex conjugation. It is the quasi-matching that provides perfect complex conjugation when only impedance magnitudes are equal, which is worse for reducing the minimum power supply voltage ($U_{\min} \sim F^{0.5}$; see above). Below, we give a description of a possible circuitry implementation of the crystal oscillator based on all these considerations.

A schematic diagram of the oscillator is shown in Fig. 1.

The circuit provides generation at the fundamental resonance of the crystal from 15 to 30 MHz.

The preliminary circuit calculation was performed using the datasheet from the transistor manufacturer and additionally measured static characteristics in the unsaturated region.

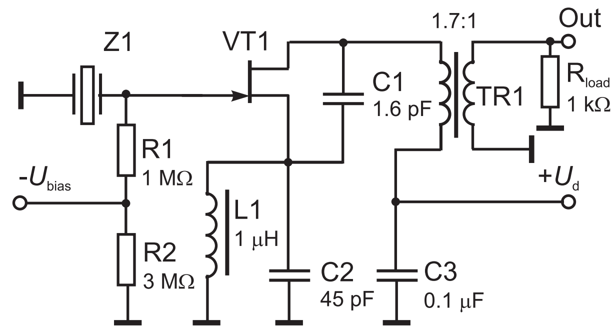

FIG. 1. Circuit diagram of the oscillator. VT1 is AVAGO ATF36077. Z1 is a general-purpose 25 MHz quartz resonator. The connection between Z1, R1, and the VT1 gate should be made as short as possible in the form of an "air bridge" not touching the printed circuit board (PCB) substrate.

The bias circuit R1, R2 (a dissipation power of about 0.1 μW) is used to adjust the optimal dc regime (gate–source voltage $U_{gs} = -0.4 \ldots -0.5$ V at room temperature and $-0.2 \ldots -0.3$ at 78 K). In addition, for practical applications, it is possible to select a zero-bias transistor for VT1.

As mentioned above, the objective of this study is to find the lower limit for a reduction in the supply voltage and, correspondingly, the power consumption.

Figure 2 displays (1) the dc drain current I_{ddc} of the quenched oscillator, (2) the dc drain current I_{dac} of the self-excited oscillator vs the drain–source voltage U_{ds}, and (3) the generated signal amplitude U_{out} vs the supply voltage U_d. Actually, $U_{ds} = U_d$. It is easy to see from the U_{out} curve that the stable generation is observed at $U_d = 17$ mV that corresponds to sub-microwatt (300 nW) power consumption. The transconductance G_m and the voltage gain

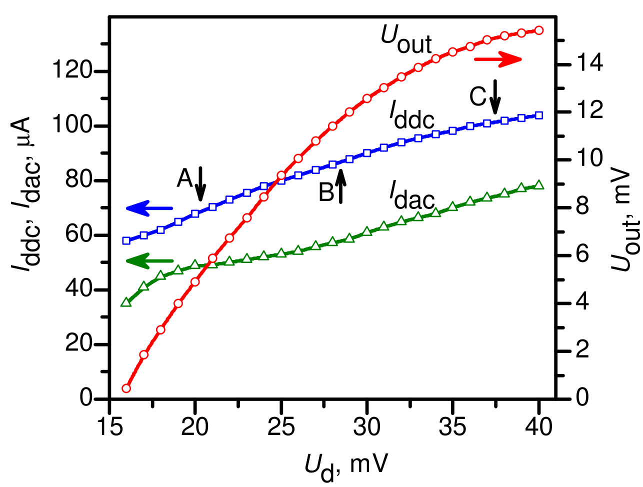

FIG. 2. Static $I_{ddc}(U_{ds})$ and dynamic $I_{dac}(U_{ds})$ characteristics of the transistor and output peak-to-peak voltage U_{out} of the oscillator vs supply voltage U_d, $U_{ds} = U_d$. For points A, B, and C indicated by vertical arrows, transconductance G_m and voltage gain G_u are 0.5 ms and 0.15, 0.7 ms and 0.35, 0.9 ms and 0.6, correspondingly.

$G_u = G_m(dI_{ddc}/dU_d)$ are shown for some U_d values indicated by letters A, B, and C. Such characteristics were not achieved earlier in the devices with similar functionality.

Notably, the self-voltage gain (with no load taken into account) for the entire I–V characteristic does not exceed 1 being close to 0.1 in the vicinity of the threshold region. This indicates the effective operation of the quartz resonator as an impedance transformer, which enables the balance of amplitudes and the self-excitation. Note that, by indirect evidence, there is a very high-quality loaded resonance. Indeed, reducing the resistance of R1 from 1 MΩ down to 0.5 MΩ causes an increase in the generation threshold by 5 mV.

The output signal waveform is close to sine because of filtering by the output transformer. The contribution of harmonics does not exceed −8 dB at supply voltages in the range of 15 . . . 50 mV. The signal amplitude is about 0.3 of the supply voltage at a 1 KΩ load. Power dc to rf conversion efficiency varies from 1% at U_d = 20 mV to 4.5% at U_d = 33 mV.

Because of the high level of $1/f$ noise attributed to HEMTs, we found it reasonable to make some spectral noise density measurements. For a rough estimate of the spectrum, here are some quantitative characteristics: Normalized oscillator spectral noise density S, dBn/Hz, is −71, −93, −108, and −113 dB at detuning 10, 100, 1000, and 10 000 Hz, respectively. The accuracy of a measurement is about 2 dB. The observed level of the phase noise at small detuning really significantly exceeds that of specialized devices based on silicon transistors and specially manufactured high-Q quartz resonators.[10] Nevertheless, the level of the phase noise itself is quite acceptable for general-purpose generators. Note that the general concept of our device is by no means focused solely on the use of HEMT. Silicon FETs with a high boundary frequency are also applicable. The HEMT is particularly interesting because it can operate at arbitrary low temperatures. Therefore, the HEMT-based oscillator can be a part of complex cryoelectronic devices, especially taking into account its ultra-low-power consumption since the refrigerating capacity of cryocoolers is very small, just microwatts below 0.1 K. To test the presented device as an element of cryoelectronics, we cooled it down to 78 K, with a corresponding correction of the bias voltage (note that there is no significant change in the amplification properties of the HEMT at lower temperatures). A decrease, down to 10 mV, in the self-excitation threshold voltage was observed, with a power consumption of about 100 nW. Thus, the oscillator can also be used in deep-cooled cryoelectronic devices, especially taking into account that the brightness noise (electron) temperature drastically falls down at the HEMT supply voltage lower than 30 mV.[11]

To summarize, this paper presents an approach to designing the ultra-low-voltage crystal quartz oscillators. The concept is based on the use of a field-effect transistor in its unsaturated mode. To implement the idea, a quartz resonator is exploited as a resonant impedance transformer.

The steady self-excitation mode was observed with the supply voltage of less than 17 mV and the power consumption as low as 300 nW, i.e., 1–2 orders of magnitude lower than the modern records. The proposed oscillator design can be recommended for use in ULP radio devices (medical and other sensors, converters, radio frequency identification systems, etc.) including cryoelectronic ones.

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DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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